

NOISE SPECIFICATIONS FOR LARGE REDUCTION GEARS
IN TERMS OF PHYSICAL UNITS

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NOISE SPECIFICATIONS FOR LARGE REDUCTION GEARS IN TERMS OF PHYSICAL UNITS

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The increasing demand for quieter machinery has introduced the problem of noise limits and noise specifications for machinery. Such specifications should obviously be based upon some physical quantity such as the dyne per sq. cm. of acoustic pressure. On the other hand, if the noise rating of a machine is to be of much practical value, it must be quite definitely related to the loudness of the sound as it appears to the average human ear. This introduces the additional factors of the psychological characteristics of the human ear concerning the relative loudness of sounds of different intensities and frequency spectra. Up to the present time there is no general agreement concerning just how these various physical and psychological factors should be combined to determine noise ratings of machinery; indeed, the published data on machine noise measurement is very meagre. This paper presents a series of measurements which were made of the sounds produced by a certain type of large reduction gear unit for the purpose of determining noise specifications for that particular type of machine. This project was sponsored and supported by The Detroit Edison Company, and the material is published through the courtesy and the permission of that company.

Program of Measurements and Methods. The type of gear unit under consideration is a large reduction unit and is shown in Figures 1 and 2.

It is driven by two steam turbines which operate at speeds of 3000 and 4000 R.P.M., respectively. Each of these turbines is direct-connected to a pinion shaft on either side of the machine. Both of the pinion gears mesh with a common large gear which is direct-connected to a 360 R.P.M., 240-volt, 4000-Kw. D.C. generator. The gears are of the double-helical type, each half of the gear being mounted separately.

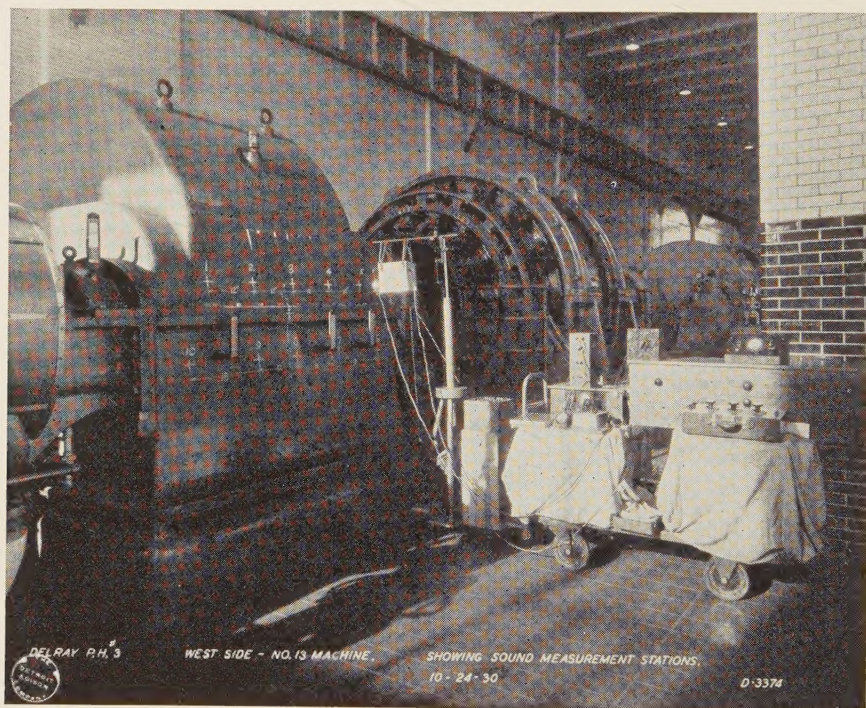


FIG. 1. One of large gear units showing measuring apparatus and location of measurement stations.

Eight identical units of this type were available for use, five at the Trenton Channel plant, and three at the Delray plant of the Detroit Edison Company. In addition to these, measurements were made on two smaller units of the type shown in Figures 4 and 5.

The sound-measuring apparatus is shown in Figure 1. A Western Electric condenser transmitter, together with a one-stage amplifier was mounted on a small truck so that it could be placed at the various measuring stations near the machine. Following this was an attenuator calibrated in decibels, a vacuum tube amplifier, and an indicating meter which was calibrated in tenths of decibels. An audio oscillator was also

provided so that the entire amplifier circuit could be calibrated before and after each set of readings by placing known voltages in series with the microphone. The frequency-response characteristic of the amplifier was adjusted to conform approximately to the "constant loudness contour" for sounds of the corresponding intensity as determined by Kingsbury.¹ By this means a weighted sum of all component frequencies was

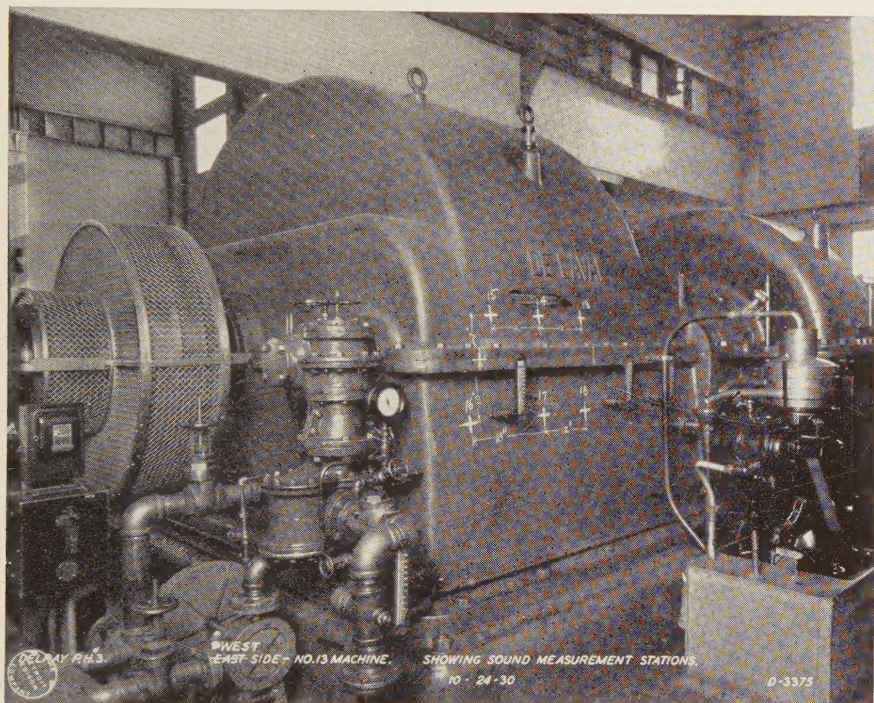


FIG. 2. Back side of large gear unit showing measurement stations.

obtained simultaneously. This sum has been called the "total noise."² These readings were recorded in terms of the 1000-cycle note which gave the same meter reading as the sound in question. This in turn was expressed in terms of decibels above the voltage corresponding to a sound pressure of .00053 dynes per sq. cm. These readings have been called "equivalent decibels above the 1000-cycle threshold." Unpublished measurements by Dr. P. H. Geiger of this laboratory indicate that for a fairly wide range of intensities and qualities of sounds, the readings obtained in this manner agree quite well with the average loudness ratings of a number of observers. The sounds from these gears

were very loud, and accordingly the 80 db. weighting curve was chosen for the total-noise meter for this investigation.

The amplifier was also provided with a manually operated frequency-analyzer which covered the audio range. The selectivity of this analyzer was slightly better than that of the human ear, so that it was possible to analyze out and measure separately any component note which could be heard by ear. With this equipment it was possible to measure the frequency spectrum of each machine, and to determine accurately the frequencies of the various component notes. The readings were recorded either in dynes per sq. cm. at the given frequency, or in equivalent db. above the 1000-cycle threshold. The equipment was mounted on a hand truck as shown, and measurements were made of each gear unit under operating conditions in the plant. Readings were made on each machine at the sixteen stations indicated in the photographs. In each case the microphone was placed six inches from the gear case. It was found that the reading at any point showed short-time fluctuations, and accordingly a slowly responding indicating meter was used, and each reading was observed long enough to obtain an average. It was possible to determine the reading of the total noise at any point to within 0.1 db., and the value of an analyzed note to within 1 db.

Total Noise Measurements. The factors which determine the loudness of the noise of any machine are so many that it is scarcely possible to express its noise rating by a single number, but the so-called "total noise" appears, in many cases, to satisfy this rather difficult requirement fairly well. Accordingly, measurements were made to determine the average total noise of each of the machines.

Variations Among Individual Observations. The various machines tested were apparently of identical construction, and it might be supposed that proper relative ratings could be obtained by placing the microphone at the same corresponding station on each machine. Such did not prove to be the case. Figure 3 shows the results of a series of measurements made at ten corresponding stations on the front sides of the eight large machines under test. The number of the station is plotted as abscissa and the total noise as ordinate. Straight lines are used to connect the values for a given machine at the different stations. The variation in noise from station to station is shown by the rise and fall of these lines across the graph. Machine 3 showed a maximum variation from station to station of 6 db., while Machine 1 showed about 2 db. The variations for the other machines fell between these two

extremes. While these variations do not seem extremely large, they were fully as great as the differences between machines.

If the machines were placed in the same order at all corresponding stations, there would be no crossing of the lines in Figure 3. It will be observed that crosses are the rule rather than the exception, and that the machines were placed in a very different order of loudness at each measurement station. For example, Machine 2, which was next to the noisiest of the group, measured the quietest of all at Stations 1 and 10, and the loudest of all at Stations 5 to 9. Machine 1, which was the quietest of the group, measured next to the loudest at Station 10 and the

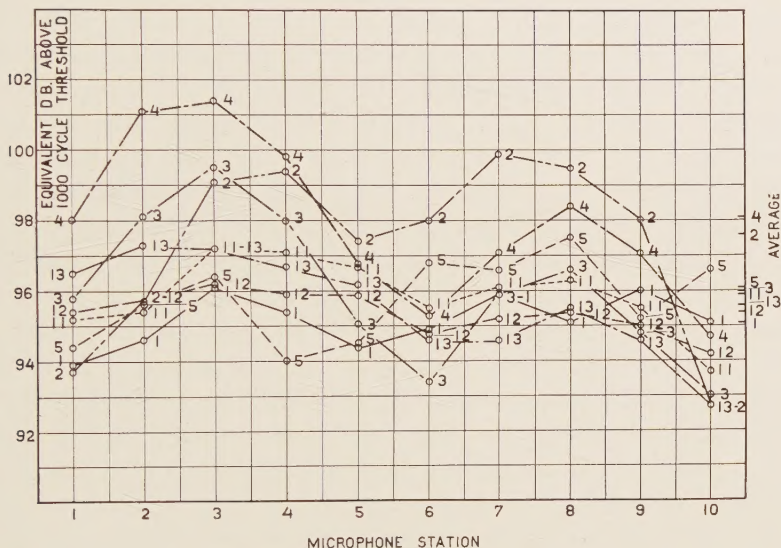


FIG. 3. Individual "Total Noise" Measurements (corrected for room noise) on the front sides of the eight large units showing variations in loudness among the ten different measurement stations.

quietest at Stations 2, 5, and 8. At Station 6, Machine 4, which was by far the loudest of the group, measured less than Machine 11, which was a fairly quiet one and practically the same as Machine 1, which was the quietest of the group.

These variations are attributed to differences in the audio-frequency vibration patterns of the various machines, and the corresponding differences in the sound wave patterns in the air surrounding the machines. These variations are not due to resonances in the ordinary meaning of the word. Resonance is usually used to indicate a large amplitude which

results from the correspondence of a periodic driving force with some natural period of the vibrating body. No evidence whatever has been found of such critical frequencies in these gear units. Instead, the phenomenon seems to be one of interference between the many reflected waves in the vibrating body which produce large variations in amplitude from point to point. A slight change of speed or other condition may greatly affect the value at any given point, but the average over a considerable region does not seem to be much affected. In spite of the fact that the machines were apparently identical, there were large differences between the wave patterns of the different machines.

Such variations seem to be quite typical of machine noises and these measurements indicate the futility of trying to obtain comparative noise ratings at a single microphone location unless means are taken to average out these effects. Among the means which have been suggested for averaging wave patterns are "warbling" the frequency several times a second, making the measurements in a highly reflecting sound chamber with a moving reflector to shift the patterns continually, and swinging the microphone. The first two of these methods were out of the question in the present case, and the third offered considerable difficulty in view of the irregular shape of the machines and the desirability of keeping the microphone close to the gear case in order to reduce the extraneous noise reaching it. In this particular instance it appeared that the value obtained by averaging the readings at the ten stations on each side of a machine would give a fairly accurate value for the noise of that machine, and accordingly, the data discussed in the following pages are these average values. It is believed that more accurate averages could be obtained by using a greater number of stations, and perhaps different averages would be obtained for stations on different parts of the machine, but those mentioned above are believed to give satisfactory noise ratings.

Average Total Noise Measurements. It was found that the readings obtained on a given machine varied somewhat from day to day, and, accordingly, from three to seven separate runs were made on each machine on different days in order to obtain an average value. The results of these measurements are shown in Table I.

The values tabulated above do not give the true noise of the various machines, because in each case a part of the reading was due to extraneous room noise which reached the microphone. This room noise was largely due to other machinery which was in operation in the station, and its value varied considerably at the locations of the different ma-

chines. Measurements showed that the room noise seldom varied more than a few tenths of a decibel from station to station on a given machine, and that the values obtained from day to day were nearly as constant provided that the same machines were running in the remainder of the station. Accordingly, the room noise was measured at the usual stations at each machine with that machine at rest, and the remainder of the station operating as it had been when the measurements

TABLE I
TOTAL NOISE MEASUREMENTS—COMBINED GEAR AND ROOM NOISE
LARGE UNITS—LOAD 8000 AMPERES

	Machine							
	1	2	3	4	5	11	12	13
Equivalent Decibels above 1000 cycle Threshold Average of Readings at Stations 1-10								
Run								
1	97.9	99.1	97.1	98.9	98.1	97.7	96.7	96.4
2	97.0	98.8	97.3	99.1	97.4	97.3	96.6	96.5
3	97.9	98.9	97.3	98.9	97.6	97.7	96.6	97.0
4	97.1		97.4			97.7	97.0	96.6
5	96.7		97.4				97.1	97.0
6	96.8		97.4				96.8	96.3
7							96.9	
Av.	97.2	98.9	97.3	99.0	97.7	97.6	96.8	96.6
Average of Readings at Stations 13-18								
1	98.0	97.6	97.1	99.1	97.7	98.2	98.1	97.1
2	97.9	97.1	97.2			98.3	98.3	97.4
3	96.3		97.4			98.9	98.0	97.0
4			97.6			98.9	98.1	
5							97.6	
Av.	97.4	97.3	97.3	99.1	97.7	98.6	98.0	97.2

of Table 1 were made. From these data it was possible to correct the previous measurements so that they indicated the noise from the machine alone. This correction was made by taking the square root of the differences of the squares of the acoustic pressures corresponding to the given readings. A number of unpublished experiments by the author and by other investigators in this laboratory indicate that such a correction is very accurate, providing that the extraneous noise is fairly constant, of different frequency than the noise to be measured, and not

much larger than the corrected noise. The results of this correction are given in Table II, with the gear units arranged in ascending order of loudness. The value recorded for Stations 1-10 on each machine represents the average of about 50 individual observations, while that for Stations 13-18 represents the average of about 30. Accordingly, the former are given double weight in computing the grand average for the machine.

TABLE II
TOTAL NOISE MEASUREMENTS—LARGE GEAR UNITS
EFFECT OF CORRECTION FOR ROOM NOISE

Ma- chine	Stations 1-10			Stations 13-18			Grand Av.
	Uncorr'd	Room	Corr'd	Uncorr'd	Room	Corr'd	Corr'd
1	97.2	93.0	95.1	97.4	91.6	96.1	95.4
12	96.8	91.2	95.4	98.0	92.6	96.5	95.8
13	96.6	89.6	95.6	97.2	90.4	96.2	95.8
11	97.6	92.7	95.9	98.6	94.2	96.6	96.1
5	97.7	92.7	96.1	97.7	92.6	96.1	96.1
3	97.3	91.2	96.1	97.3	89.8	96.4	96.2
2	98.9	93.1	97.6	97.3	93.8	94.7	96.6
4	99.0	91.6	98.1	99.1	90.2	98.5	98.2

The outstanding result of these measurements is the very small range of values. The difference between the quietest machine and the loudest amounts to 2.8 db., and it might appear that there is no appreciable difference in the loudness of the group of machines. Such is by no means the case. The first time the author heard these machines he listened to Machines 12 and 13, after which he rode 20 miles in an automobile to another station to listen to Machine 4. With no previous suggestions concerning the relative loudness he instantly and unhesitatingly pronounced it much louder than the other machines. This observation has been fully confirmed by plant engineers. Machines 1 to 5 are all located in the same plant, and by operating them all simultaneously it was possible to pass back and forth from one to the other and compare the relative loudness by ear. The results of these observations were in perfect agreement with the above measurements. Machine 1 was noticeably the quietest, Machines 3 and 5 were somewhat louder, Machine 2 was still louder, and Machine 4 was very noisy. Reference to the published data on minimum perceptible differences³ shows that for sounds of this

of this level, the minimum perceptible difference in intensity is about .3 db. compared to approximately 1 db. for sounds of ordinary intensity. Accordingly, the 2.8 db. between the quietest and the loudest machines would sound much the same as a 10 db. change at lower levels. This latter figure is a very large change in the case of machine noises, and would be very easily remembered.

The corrected data of Table II show that the noise on the back side of the machines (Stations 13-18) averaged about 0.7 db. greater than on the front side (Stations 1-10). This was attributed to a larger amount of reflected sound from a nearby wall. The back sides of the machines were about eight feet from a hard tile wall, while it was several times this distance to any large reflecting object on the front sides of the machines. Machine 2 differed from the rest in that the noise was 2.9 db. less on the back than on the front. This was due to the peculiar quality of the sound from this unit which was brought out more fully by frequency analysis. Another interesting result of these measurements was the large value of the room noise. This averaged about 92 db., or 3.5 db. less than the quietest machine. It was possible to observe how great this change appeared by placing the ear close to the machine, and then moving away from it, or by listening at a given point with the machine stopped and then with it running. These observations were all in accord with the above measurements.

Although the above measurements seemed very consistent, the author was somewhat perturbed by the small range of values. Accordingly, arrangements were made to measure the noises from a pair of reduction gear units like those shown in Figures 3 and 4. Each of these units is driven by a single steam turbine which operates at 3710 R.P.M. The slow-speed end is direct-connected to a 514 R.P.M., D.C. Generator. The gears are of the double helical type, and the two halves are mounted separately as shown in the pictures. The H.P. rating of these sets in about $\frac{1}{3}$ that of the larger units. Several runs were taken on each of these machines and the average results are shown in Table III.

The size and shape of these units varied considerably from those of the other units, and the quality of the sound was considerably different. By ear, Machine 5 appeared to be very quiet, and Machine 6 extremely noisy. The measured difference was 4.4 db. which is consistent with the previous data. The author was very agreeably surprised to find that these two units were of the same order of loudness as the other machines. The less noisy of the two machines was 1.0 db. quieter than the quietest of the other group, and the noisier was 0.6 db. noisier than the

TABLE III
TOTAL NOISE MEASUREMENTS—SMALL GEAR UNITS

Machine	Stations 1-10			Stations 11-20			Grand Av.
	Equivalent Decibels Above 1000 Cycles Threshold						
	Uncorr'd	Room	Corr'd	Uncorr'd	Room	Corr'd	Corr'd
5 (small)	95.8	88.1	95.0	95.2	89.8	93.7	94.4
6 (small)	99.5	82.0	99.4	98.5	81.6	98.4	98.8

noisiest of the other group. It was found that the room noise at the locations of these two machines was less than at the others, which was also in agreement with aural observations.

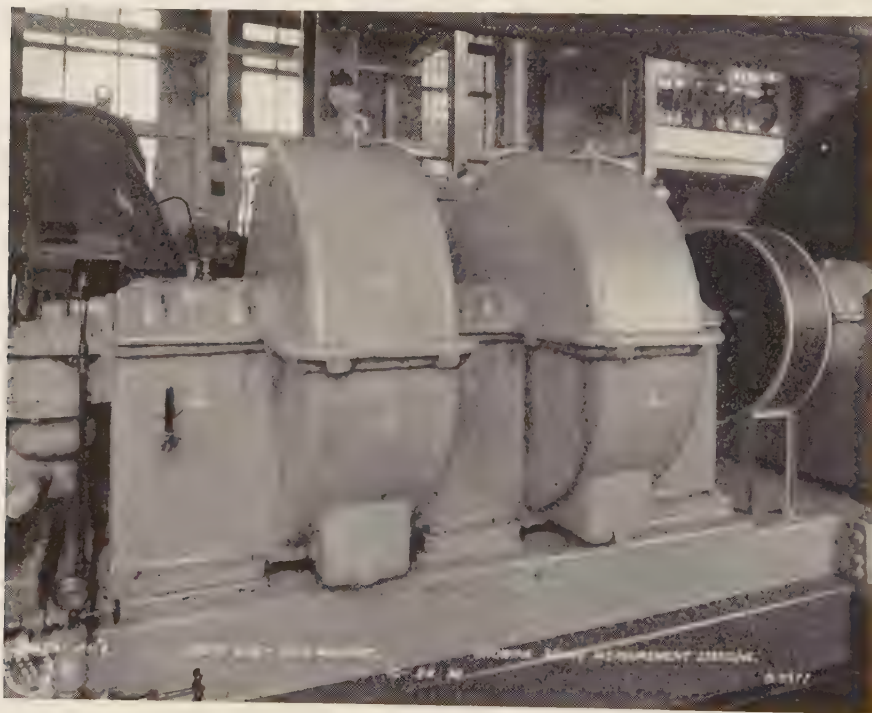


FIG. 4. Front side of one of small gear units showing the location of the measurement stations and the irregular shape of the enclosing case.

The differences between the measurements of the different machines were somewhat less than had been anticipated. The principal conse-

quence of this small difference is the necessity of unusually accurate calibration of the microphone in terms of absolute units. The data indicate that the difference in total noise of a machine which would be accepted under the specification and one which would be rejected might be only one or two decibels. Accordingly, the absolute calibration should certainly be correct within $\frac{1}{2}$ db. and preferably within $\frac{1}{4}$ db.

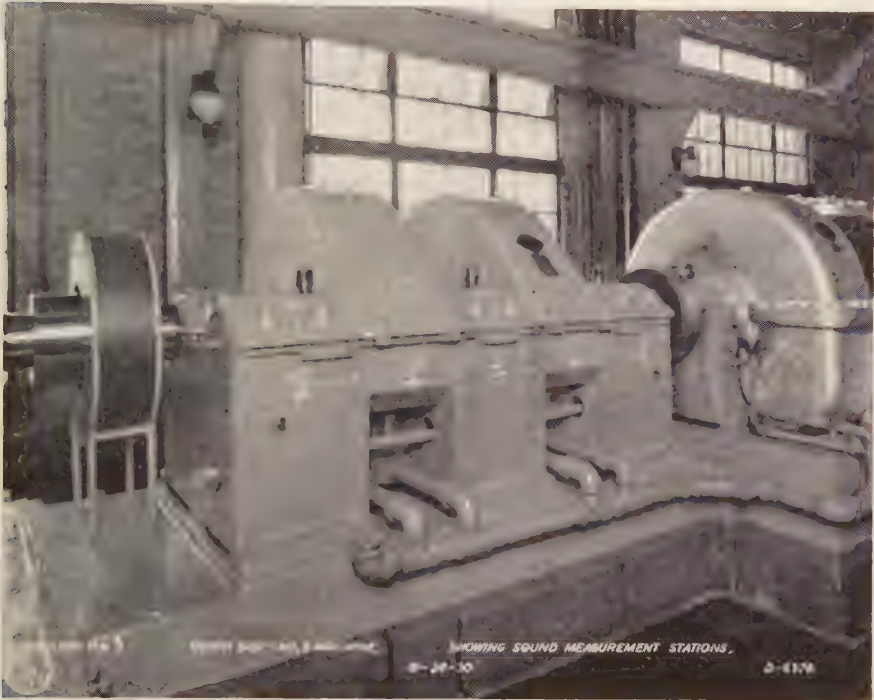


FIG. 5. Back side of one of small gear units.

Apparently this represents a rather unusual accuracy in microphone calibration. On the other hand, the results obtained were consistent with themselves and with the published information on the characteristics of the average human ear. It was concluded that, if proper precautions were taken to average out the variations from point to point and from day to day, the average total noise furnished one satisfactory noise rating for these machines.

Frequency Analyses. Although the total-noise measurements described above furnish one suitable value for rating the noise of these gear units, they by no means furnish all of the information which can

be gained from sound measurements. It was arranged, therefore, to make a frequency analysis of the noise from each machine. The microphone was placed at one of the central stations on the machine, and the tuning of the analyzer was varied until a large reading on the meter indicated the presence of a musical note. Measurements were then taken at each of the ten stations previously described. This process was repeated until each of the component frequencies of the sound of the machine had been determined. Analyses were made on both sides of

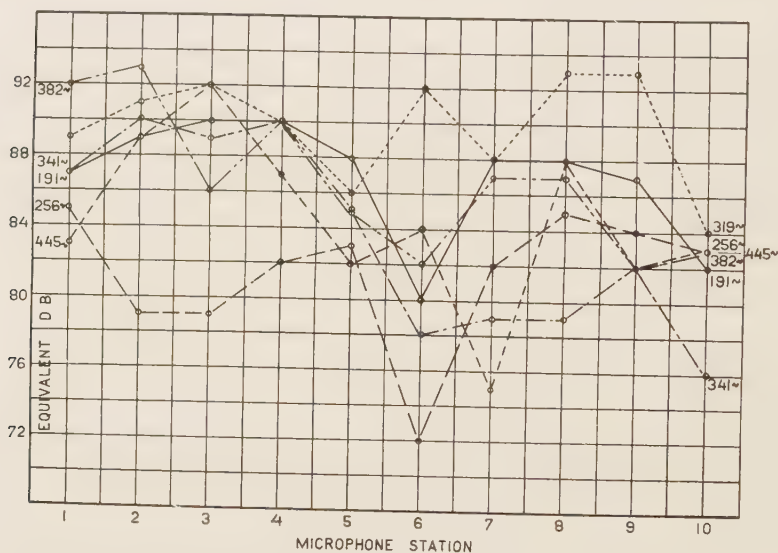


FIG. 6. Individual readings of six different analyzed notes at the ten measurement stations on the front side of Machine 4.

the two small gear units. No important differences were noted between the analyses on the two sides, so that analyses were made on only one side of the eight large units.

Variation Among Individual Readings. It was found that the reading on any particular note varied considerably from point to point on the machine. Figure 6 shows the readings obtained on six different notes at each of the ten stations of Machine 4. It will be observed that the variations range from 5 to 15 db. which variation is considerably larger than in the case of total-noise measurements. It will also be observed that the point-to-point variation is different for every note.

It was found that seven of the eight machines produced a note of 260 cycles, although the relative importance of this note varied consider-

ably from machine to machine. Figure 7 shows the measurements obtained for this note at each of the ten stations of the seven machines. It will be observed that there is more of a resemblance in the pattern formed by a given note on the different machines than there is between the various notes on a single machine. There are plenty of crosses in the graph, however, showing that there is considerable variation among the different machines. This no doubt accounts for the variations observed in the case of total noise. The variations are smaller in the case of total-

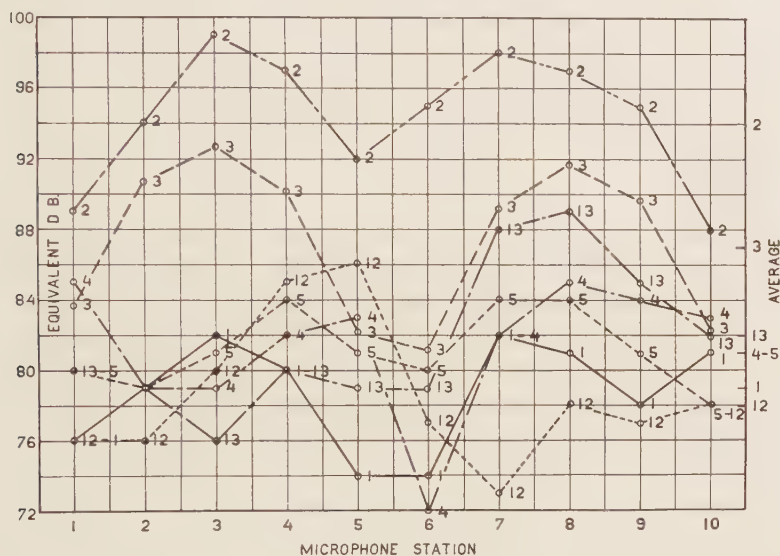


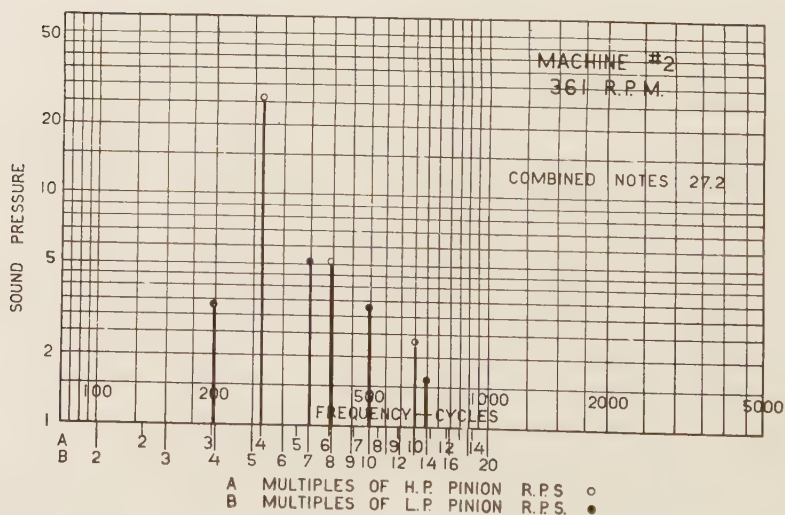
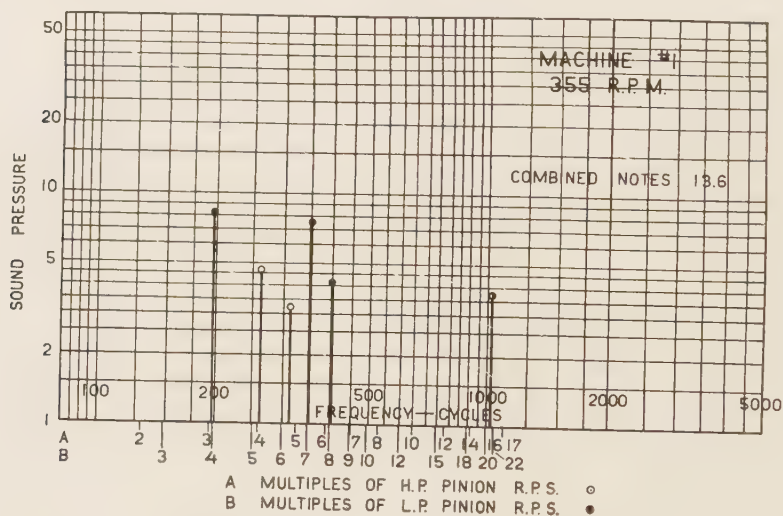
FIG. 7. Individual readings of the 260 note (4th. harmonic of high pressure pinion) at the ten microphone locations on the front sides of the eight large machines.

noise measurements on account of the averaging effect of the patterns of different frequencies. For this reason the value obtained for an individual component is not as accurate as the value for the total noise, and, accordingly, the analyzed notes are recorded to the nearest decibel instead of the nearest 1/10 decibel. The data hereafter described represent the average of the ten stations on each machine exactly as in the case of total noise.

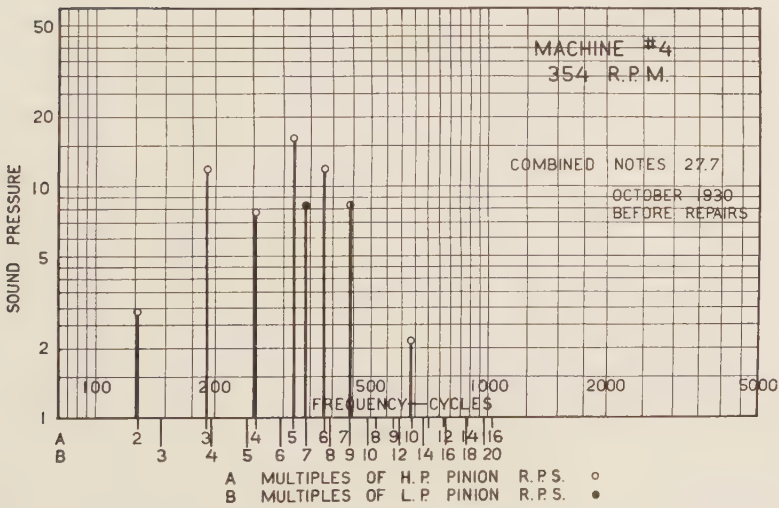
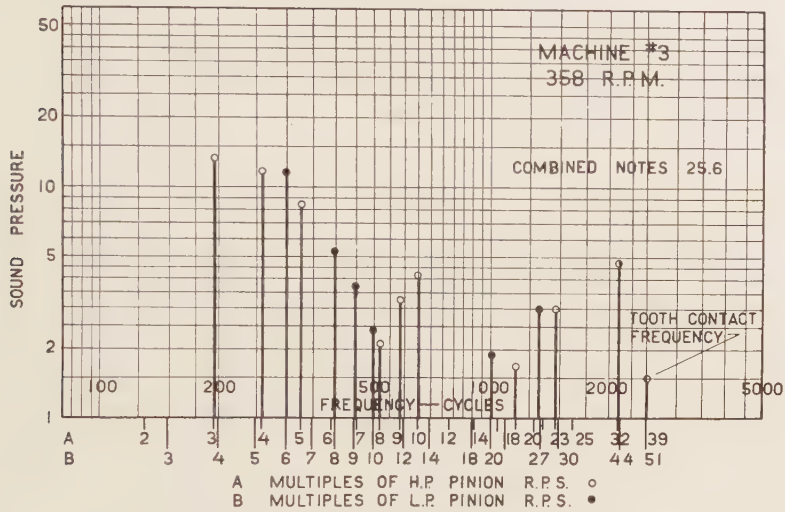
Average Measurements of Analyzed Notes. The frequency analyses of the eight large units are shown in Figures 8 to 15. The frequency of the observed note is plotted as abscissa, and the acoustic pressure in dynes per square centimeter is plotted as ordinate. The number of notes which could be distinguished on each machine varied from six in the

case of Machine 1, to sixteen in the case of Machine 3. Strangely enough the total noise of these two machines measured within a few tenths of a decibel of the same value.

Every machine showed an individual frequency spectrum. For example, most of the musical sound from Machine 2 was concentrated in a single note at 260 cycles, while Machine 12 showed a large group of notes of approximately the same pressure extending from 150 cycles to above 2,000 cycles. Machine 4 showed no components whatever above

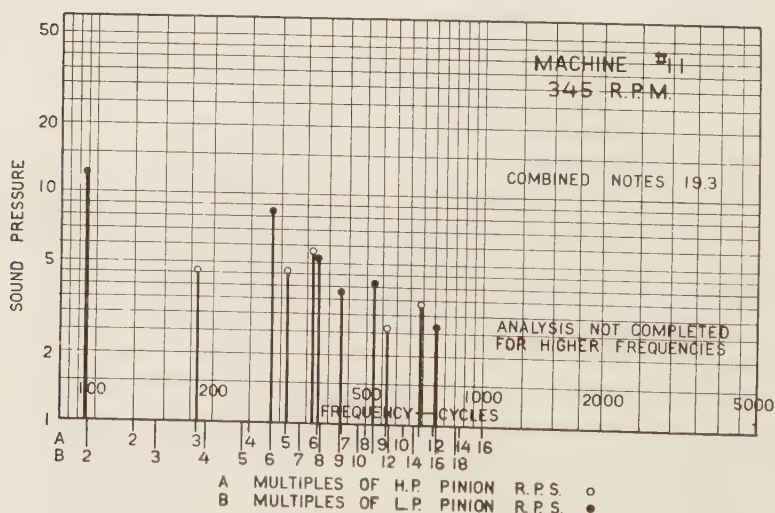
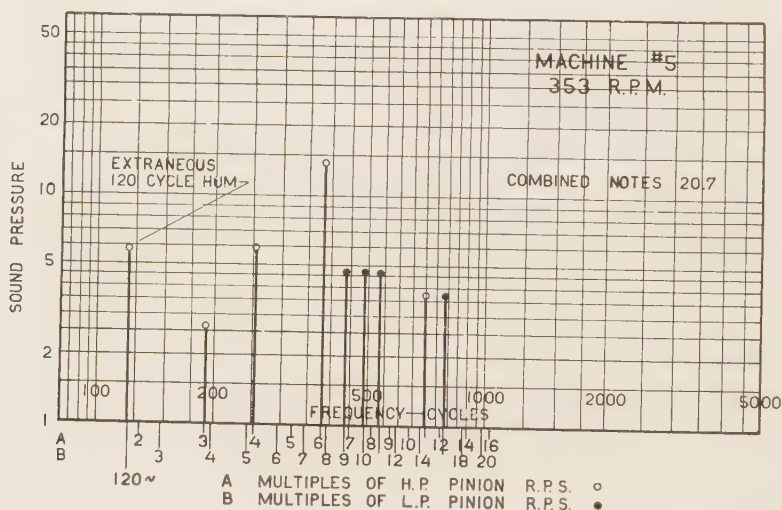


600 cycles and practically all of the musical sound was produced by a group of six notes between 200 and 450 cycles. It will also be observed that while all of the notes of the different machines lie in the same frequency region, that the frequencies of the individual components are, in general, different for every machine. In case a given note appears in the spectrum of more than one machine, its relative importance is dif-



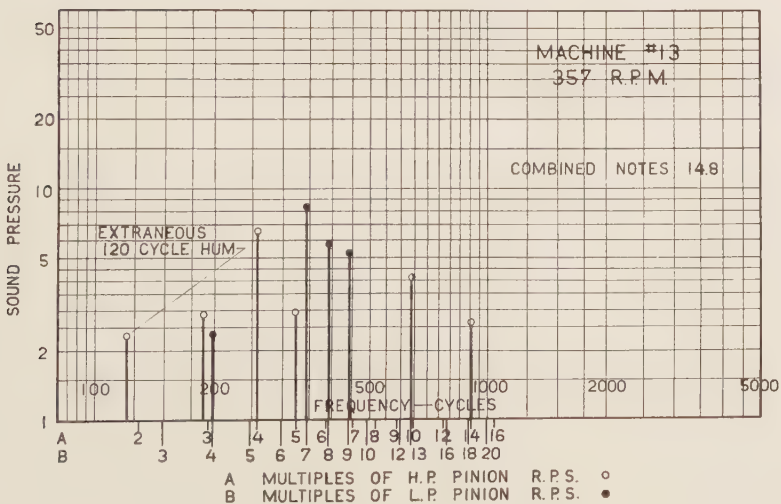
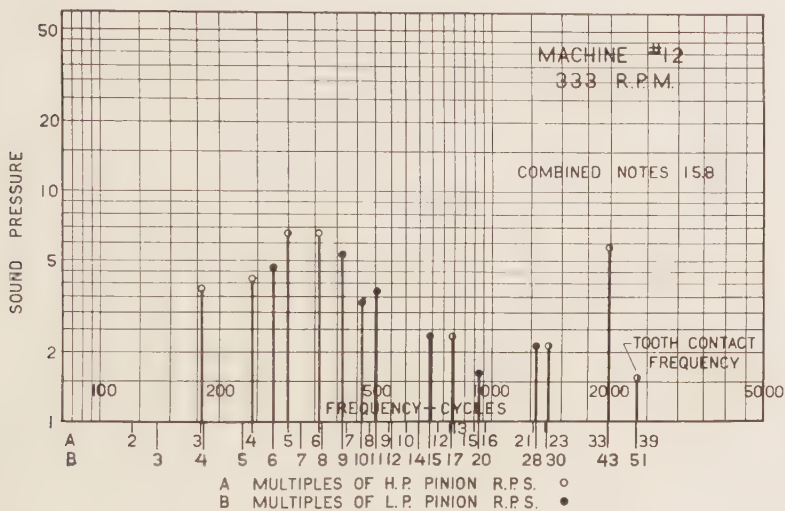
ferent for each machine. These results account for the individual character of the sound from the different gear units.

The frequency analyses of the two smaller units are shown in Figures 16 to 19. These machines showed a group of notes similar to those of the large units except that most of the important notes were in the region from 600 to 1200 cycles instead of 200 to 500 cycles. As a result,



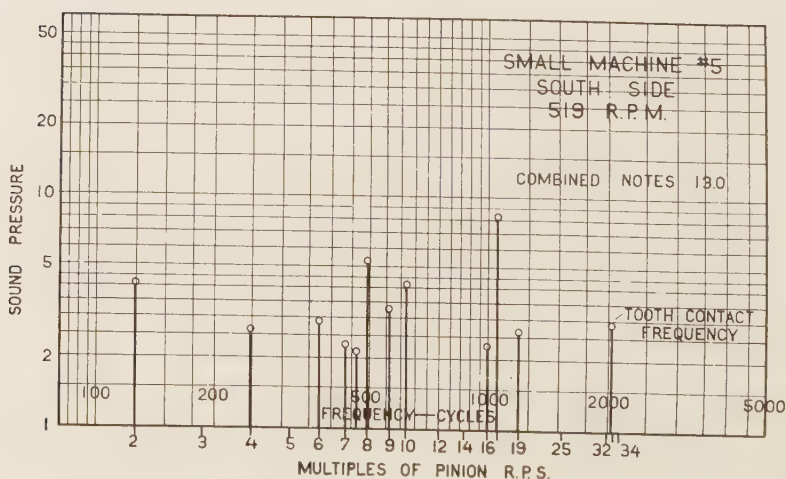
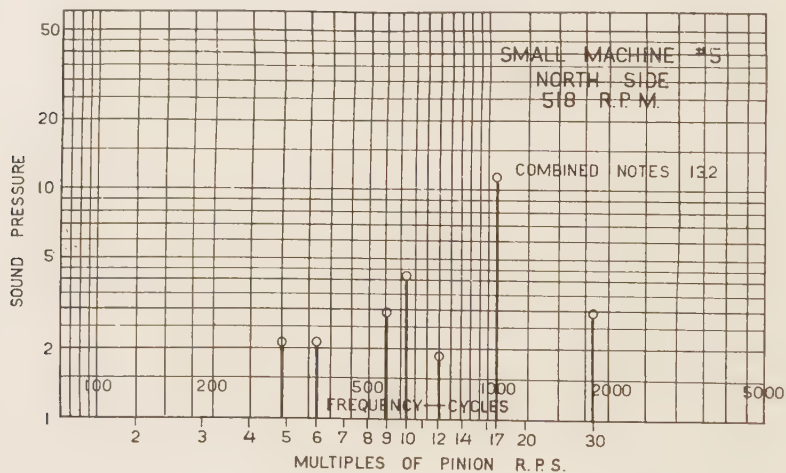
the noise from these units appeared to be pitched one or two octaves higher than did that of the large units.

It is not apparent just why this should be the case. The pinions on the large machines run at 3000 and 4000 R.P.M. and have 51 and 39 teeth, respectively, while the pinion on the small machines runs 3710

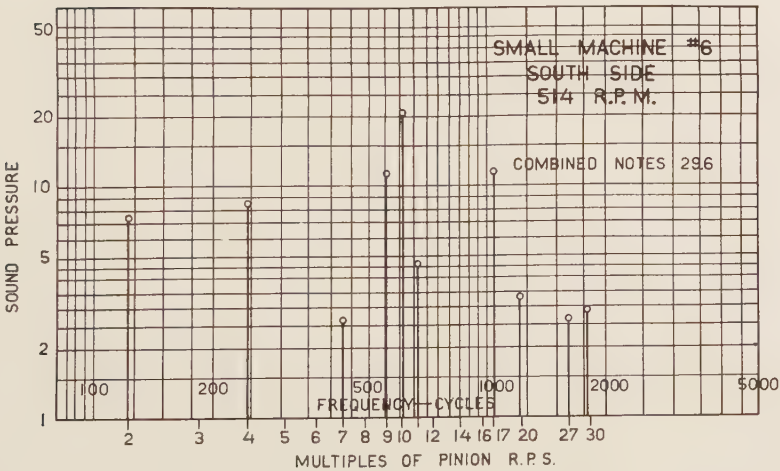
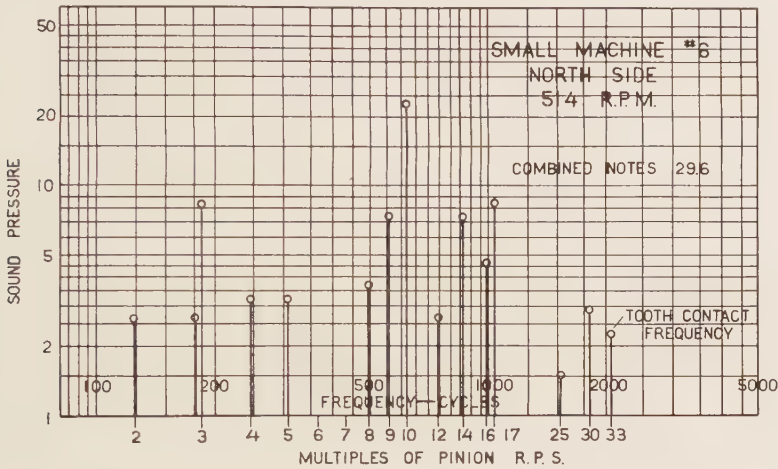


FIGS. 8 to 15 *Frequency analyses of the musical notes on the front sides of the large gear units. Averages of Stations 1 to 10.*

R.P.M. and has 33 teeth. These facts would appear to favor higher notes on the large machines. Reference to the graphs shows that the lower frequency components are present, but they are not as loud as the others. The explanation may lie in the different construction of the main castings of the gear cases. As shown in the photographs, the enclosing case of the smaller units conforms to the gears, and is quite irregular and has no large flat surfaces. The shape of large units is essentially rectangular with a smooth curved top and large flat surfaces. These may be more effective in radiating the longer wave lengths of sound than are the smaller surfaces of the smaller units.



Noise Specifications. The total noise measurements and the frequency analyses described above furnish the necessary data for a noise specification of these machines in terms of four different characteristics. These are the "total noise," the "largest single note," the "combined musical notes," and the "unpitched sound." The meanings of the first two of these are obvious as they are obtained directly from measurement. The other two were computed as follows: The values of the sound pressures of the individual notes were first weighted according to their



FIGS. 16 to 19. Frequency analyses of the musical notes on the small gear units

relative loudness as determined from the data of Kingsbury.¹ The value which represents the combined musical notes of each machine was then computed by taking the square root of the sum of the squares of these weighted sound pressures. In every case this value was found to be less than the measured total noise. This difference was due to the presence of sounds which had no particular frequency and which were due to roughness, differences among teeth, and other irregularities. Such

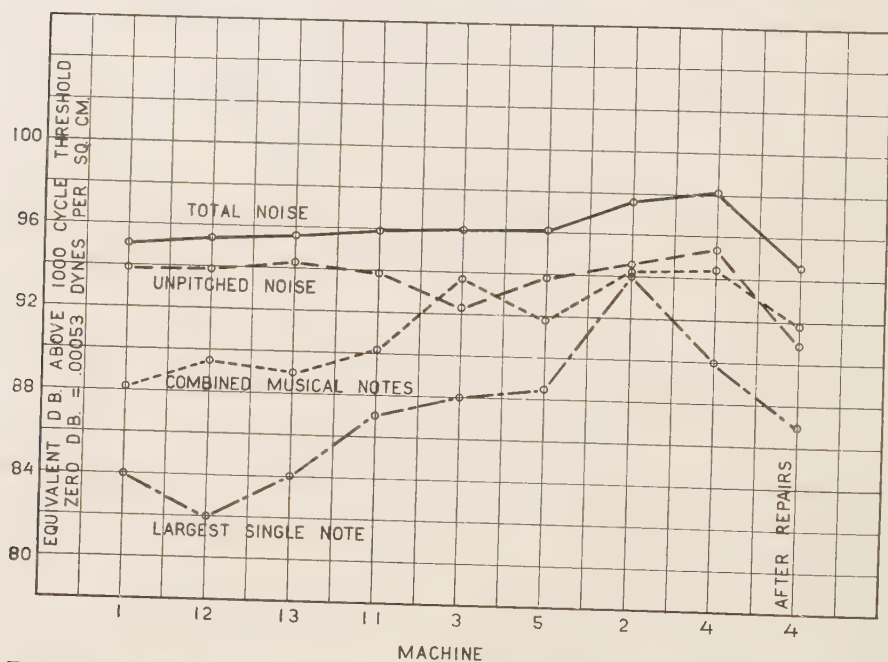


FIG. 20. Large units arranged in order of total noise, and showing relative amounts of total noise, unpitched noise, combined musical notes, and largest single note. These four characteristics were used for noise specifications. The effects of repairs on Machine 4 are also shown.

sounds are technically known as “unpitched sounds.” The value of the unpitched sound for each gear set was computed by taking the square root of the difference of the squares of the total noise and the combined musical notes. These four values for each machine are shown graphically in Figure 20. Figure 20 also shows readings which are marked “Machine 4 after repairs.” These measurements are described in the following section of the paper.

The values obtained show a range of 12 db. for the largest single note, of 6 db. for the combined musical notes, of 3 db. for the total noise, and of 1.5 db. for the unpitched sound. From this it appears that the

principal difference between the quieter machines and the louder ones lies in the amount of musical notes. Inasmuch as frequency analyses are ordinarily not much affected by room noise, this fact would enable noise ratings to be made on the basis of frequency analyses in places where the room noise is too great for total-noise measurements. It will be observed that the relative amount of the four noises is different for each machine. For example, Machine 3, shows by far the smallest amount of unpitched sound, a moderate value for the largest single note, and a very large value for the combined musical notes. This is due to the large number of notes of medium loudness as shown in Figure 10. Machine 2 shows by far the largest single note, but this represents practically all the musical sound for this machine. Machine 4 was the noisiest of all the machines except in the case of the largest single note, in which respect it stood second loudest.

In order to write a noise specification it is necessary to determine which characteristics of the sound should be specified, and to select the limiting values for acceptance. This paper deals primarily with the former, because the latter depends principally upon the desirability and the cost of obtaining a given standard of quietness. Accordingly, three typical specifications are listed in Table IV.

TABLE IV
TYPICAL NOISE SPECIFICATION FOR UNITS UNDER TEST

Specification	1	2	3
	Equivalent Decibels above 100 Cycle Threshold		
Total Noise	95	96	96
Largest Single Note	84	87	89
Combined Musical Notes	88	90	94
Unpitched Sound	94	94	94
Machines Passed	#1	#1, 12, 13, 11	#1, 12, 13, 11, 3, 5
Machines Rejected	all others	#3, 5, 2, 4	#2, 4

The first of these specifications would pass only machines equal to or better than the most quiet one of the group tested. The second specification would require a new machine to be as quiet as the median machine of the group, while the third would pass the six quieter machines which are considered by the plant engineers to be satisfactory, and would reject the two machines which are definitely much noisier than the others. Of course, a complete specification would include the loca-

tion and number of measurement stations used to obtain proper averages.

These specifications meet the two requirements of a physical basis for the measurements, and a consideration of the characteristics of the average human ear. The system is related to absolute units by the choice of the "zero" of the decibel scale as a sound pressure of .00053 dynes per sq. cm. at 1000 cycles. The human ear is taken into account by the use of the decibel scale which is a fairly good loudness scale, and by the frequency weighting of the total-noise meter and the analyzed notes. The very complex question of quality is handled by making separate determinations of the four quantities described above. It is not claimed that this treatment takes account of all the characteristics of the human ear, or that such specifications would be adaptable to all problems. It does appear, however, that this method yields definite numerical values by means of which the noises of these machines may be specified and compared, and it is believed that this same method can be applied to many types of machinery noise.

TABLE V
FUNDAMENTAL MACHINE MOVEMENTS OF LARGE GEAR UNITS AT 360 R.P.M.

Part	R.P.M.	Teeth	Frequency of Fundamental Note Cycles per Second
Output shaft	360	—	6.0
Large gear	360	424	2544.
Low speed input	2993	—	49.9
Low speed pinion	2993	51	2544.
High speed input	3914	—	65.2
High speed pinion	3914	39	2544.

The Sources of Sound and the Effects of Repairs on Machine 4. In addition to furnishing an essential part of the data for noise specifications, the frequency analyses also yield very valuable information concerning which parts of the mechanism are responsible for the different noises and also something of the nature of the defect which produces the sound. This is accomplished by relating the frequencies of the observed notes with the movements of the various parts of the machine. Table V shows the frequencies of the various elements of the large gear units.

In practice the units are not operated exactly at 360 R.P.M., and therefore, the speed of each machine was measured by means of a tachometer at the time the sound measurements were taken. The series of figures at the bottoms of Figures 8 to 19 which are labelled "multiples of pinion rotation" were computed from this tachometer reading and the number of gear teeth. The frequencies of the observed notes were determined by observing the analyzer setting which gave the maximum reading on a given note, and this was translated to cycles per second from the analyzer calibration. It will be noted that in every case the observed frequency of each note corresponds to one of the multiples of pinion rotation. The differences between the observed frequencies and the computed frequencies are very much less than the probable inaccuracy of setting the analyzer and measuring the speed. In the case of Machines 5 and 13 an additional note was found which did not correspond to one of these multiples of pinion rotation. The frequency of this note was 120 cycles, so that it obviously was a magnetic note produced by 60-cycle equipment in the station. This particular note showed unusually small variations from station to station on the gear unit, which was additional evidence that it was not a gear note.

In most of the cases it was possible to determine definitely which pinion was responsible for a given note. Those due to the high-speed pinion have been marked with an open circle, and those due to the low speed with a solid circle. In certain cases where both pinions produced harmonics which were very close to the observed note, the reading has been marked with a half open and half solid circle. It is believed that with more careful measurements it could be determined just which pinion was responsible for these questionable notes. In certain cases very definite beats were noticeable between such harmonics.

The results of these analyses were very surprising to the author because the loudest notes corresponded neither to speeds of rotation nor to the frequency of tooth contact. Evidently the various shafts were in good mechanical balance because no fundamental notes of rotation whatever could be detected and nothing less than the third or fourth harmonics appeared to be important. Ordinarily the most important gear noises are those of tooth-contact frequency and its harmonics. In this case both pinions meshed with the common gear, so there was only one fundamental tooth-contact frequency at 2544 cycles. This corresponds to the 51st multiple of the low-speed pinion and the 39th multiple of the high-speed pinion. For this reason it was expected that important musical notes of the frequencies 2544, 5088, 7632, etc. would be

found. Such did not prove to be the case. None of the higher harmonics were found on any machine, and only two of the machines (3 and 12) exhibited a fundamental note of 2544 cycles. In both of these cases the fundamental gear note was more than 25 db. below the total noise of the machine. This is about as small a component as it is possible to detect either by ear or with the instrument, and, therefore, these notes were entirely negligible in comparison with the other notes on the machines.

The absence of tooth-contact frequency notes was very important as it eliminated certain very important sources of noise. Such notes arise from vibrations which occur with each contact and which are usually due to peculiarities in tooth form, to inaccuracies in alignment or mounting, or to deflections in the shaft between the two halves of the herringbone which tend to throw the gears out of adjustment. As these notes were not present, it was apparent that none of the noise was due to these most common causes of gear noise. It was also obvious that the noise was not due to a defect on any particular tooth because the frequencies did not correspond to those of rotation nor to contacts of any integral number of teeth. For example, the third harmonic of the high-pressure pinion, which was one of the more prominent notes, corresponded to 1.7 tooth-contact intervals. It also was clear that the large gear was not responsible for very much of the noise as none of the observed notes corresponded to its speed of rotation. Thirty-nine revolutions of the gear or $6\frac{1}{2}$ seconds were required to bring the same teeth on the gear and high-speed pinion in contact again. Fifty-one revolutions of the gear or $8\frac{1}{2}$ seconds were required between successive contacts of a given pair of teeth on the large gear and the slow-speed pinion. No fluctuations in the sound were observed at either of these intervals, so that no evidence whatever was obtained that the large gear was responsible for any of the musical notes. It doubtless was responsible for part of the unpitched sound, however. With the most probable sources of gear noise eliminated, it appears that the noise from these gears was largely due to peculiarities in the machine on which the pinions were cut. These errors were most probably in the mechanism by which the cutting machine was indexed from one tooth to the next, and by which the tooth spiral was generated.

As soon as the above series of measurements was completed, Machine 4, which was by far the noisiest of the group, was dissassembled for inspection. It was found that the large gear was rather rough and pitted,

but that this pitting bore no relation to the frequencies of the observed notes. The pinions also showed peculiar markings. These markings appeared in the form of dark spots which covered $\frac{1}{4}$ to $\frac{1}{2}$ the profile of the tooth, and which appeared to come in more or less definite groups. These groups of spots did not follow along a given tooth for any great distance, but instead were spread axially across the face of the gear. The width of these axial bands of spots varied from 1 to as much as 5 tooth pitches, and varied both in width and intensity across the face of the gear. In spite of these variations there were very definite regions of these axial groups of spots. Marks were placed across the centers of these groups, and it was found in the case of the low-speed pinion that there were seven of these groups almost equally spaced around the circumference of the pinion. Referring to the frequency analysis of this unit shown in Figure 11, it is found that the only note of consequence from the low-speed pinion was the 7th harmonic. This was a great triumph for the theory of harmonic analysis.

On the high-speed pinion it was found that the bands of spots were more distinct, but not as evenly spaced. They divided the circumference approximately into fifths except that one of the groups was missing. It would be expected that this would give a rather irregular sound consisting of a number of components centering around a large 5th harmonic. By referring to Figure 11 it will be seen that this was exactly the case.

Following this inspection, the gears of Machine 4 were shipped to the manufacturer for repairs. These repairs consisted of taking a very light cut from that side of the teeth which was ordinarily used. This cut was sufficient to remove the black spots and roughness mentioned above, and most of the pitting. The gears were then returned, assembled and lapped, and the machine run in for several weeks. Following this, measurements were made to determine the effect of these repairs on the noise of the machine.

The relative sound ratings of this machine before and after repairs are shown in Figure 20. It will be observed that the repairs produced an enormous reduction in the noise of this machine. The average total noise and the unpitched noise were each reduced by $3\frac{1}{2}$ db. making it the quietest of the group in respect to these two characteristics. The reduction in the unpitched noise produced a marked improvement in the smoothness of the sound, or as one of the engineers rather aptly remarked, that it had a more "healthy" sound after repairs. The value

of the combined musical notes was reduced $2\frac{1}{2}$ db. making it equal to Machine 5 in this respect, while the largest single note was reduced by 3 db. making it equal to Machine 11.

Not only were the amounts of these various sounds greatly reduced, but the character of the sound was greatly changed. The frequency analysis after repairs is shown in Figure 21. It should be compared with Figure 11, which was taken before repairs. Ten notes were distinguishable after repairs compared with eight previously, but they were not nearly as large. Before repairs all of the important notes were between 200 and 450 cycles, but afterwards notes as high as 2000 cycles were ob-

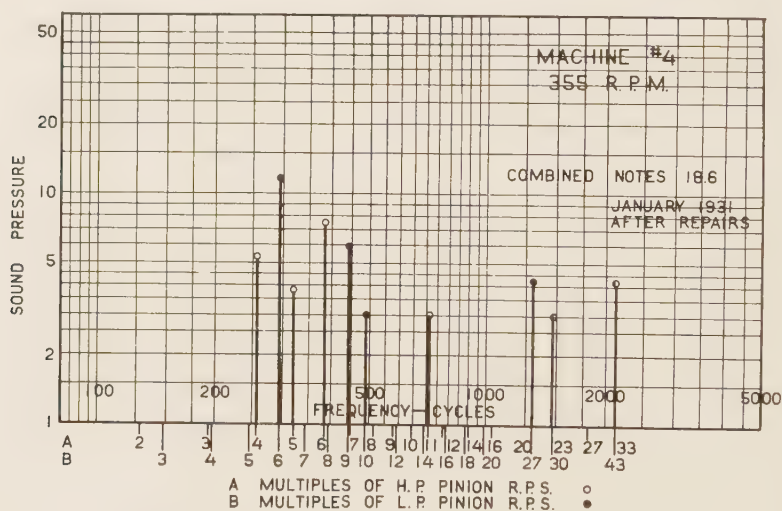


FIG. 21. Frequency analysis of Machine 4 after repairs.

served. Before repairs all but one of the important notes were due to the high-speed pinion, but afterwards both pinions contributed about equally, the largest note being produced by the low-speed pinion. An altogether different set of harmonics were present after repairs. For example, the 6th harmonic of the low-pressure pinion, which was the most prominent note after repairs, did not appear originally. The 5th harmonic of the high-speed pinion which was the most prominent note before repairs was reduced about 13 db. and was relatively unimportant after repairs. In other words, the sound spectra before and after repairs were as different as between any two machines measured.

This is very definite evidence that the musical notes observed were not due to resonance. The casing, shafts, bearings, and even the gears

themselves, with the exception of a few thousandths of an inch of material on one side of the teeth, were entirely identical before and after repairs. These include about the only parts in which one could conceive a resonance, and, since the observed notes were altogether different, it is quite evident that they were not due to resonance. Tooth-contact frequency notes were not present either before or after repairs, so that the noise was not due to errors of tooth form, adjustment, or deflection under load. The teeth were not hardened so that the errors were not due to distortions from heat treatment. From this it appears that the errors were most certainly introduced by peculiarities in the machine on which the gears were cut. The fact that the frequencies of the notes produced before and after repairs were entirely different indicates that the re-cutting of the gears removed the original defects and introduced different and smaller ones. It should prove profitable, therefore, to look for periodic errors in indexing and in tooth spiral angle in the cutting machine which might be due to gear trains or similar causes.

As shown in Figures 9 and 20, practically all of the musical sound, and a large part of the total noise of Machine 2 was concentrated in a single note of 260 cycles. This was very obviously the 4th harmonic of the high-speed pinion. Without doubt this pinion contains errors which occur about 90 degrees apart, and it is believed that evidence of these errors would be obtained on inspection. The other notes from this machine were very small, and, as shown in Table II, the total noise on the side of the machine away from this part (Stations 13-18) was nearly 3 db. less than on the front side. This accounts for the fact that this was the only machine whose total noise was less on the back side than it was on the front. As a result it is believed that if the errors in this one comparatively small part of the machine were corrected that it would be one of the quietest of the group instead of the next to the noisiest.

From such considerations it appears that frequency analysis is a very important and valuable tool for the study of machinery noises. It furnishes a means of computing the unpitched sound which cannot conveniently be measured directly, and it allows fairly satisfactory inspections to be made in noisy places where total-noise measurements are not feasible. It often furnishes very definite information concerning which particular parts of the machine are responsible for the various observed noises, and at the same time indicates very frequently the nature and the source of the defects which produce the noises.

Miscellaneous Tests. The principal part of this investigation consisted

of the measurement of the total noise and the making of frequency analyses of each machine as described above. In addition to this, a few supplementary tests were made to obtain an idea of the probable importance of some of the variables which might have affected the readings.

Additional Room Noise Measurements. The method of correcting the total noise for the extraneous room noise which was used above was selected on the basis of the preliminary measurements shown in Table V.

TABLE V
TOTAL NOISE MEASUREMENTS NEAR MACHINE 2

	Location with Respect to Station 8	Total Noise, Decibels Above 1,000 Cycle Threshold
a.	8" from case	100.1
b.	20" from case	97.6
c.	40" from case	95.6
d.	100" from case	95.6
e.	10'-6" from case	94.0
f.	17' out, 6' north	92.2
g.	5' out, 12'-4" north (beside turbine)	90.4
h.	3' out, 15' south (beside generator)	92.2

It was observed by ear that at Station "f" most of the noise came from machinery other than the gear unit, and, accordingly, this was assumed to be the approximate level of the room noise. This was well born out by the subsequent measurements shown in Table II. It was also observed that the noise was no greater than this value at stations near the turbine and the generator which showed that these machines did not add greatly to the noise measured near the gear unit.

A more careful test of this same type is shown in Figure 22 where readings were made at 34 selected stations in the neighborhood of Machine 12. Not enough stations were taken to average-out the point-to-point variations, but from these data it appears that the loudness in the neighborhood of the generator was about the same as that near the gear unit (one of the quieter units). The noise was slightly less in the neighborhood of the turbine and still less out in the open part of the room. These measurements agree very well with observations made by ear and indicate that the D.C. generators are responsible for an appreciable part of the room noise. Strictly speaking, the room noise which was used for correcting the total noise should include that from

the adjacent generator. No means were available for driving this generator without the gears and since the correction was small and the room noise came from a half dozen or more different machines it is not believed that this error was appreciable.

Effect of Microphone Location. While taking measurements it was observed that a difference of an inch or so in the position of the microphone usually made little difference in the readings. The first two figures in Table V indicate that a factor of $2\frac{1}{2}$ in the distance from the gear

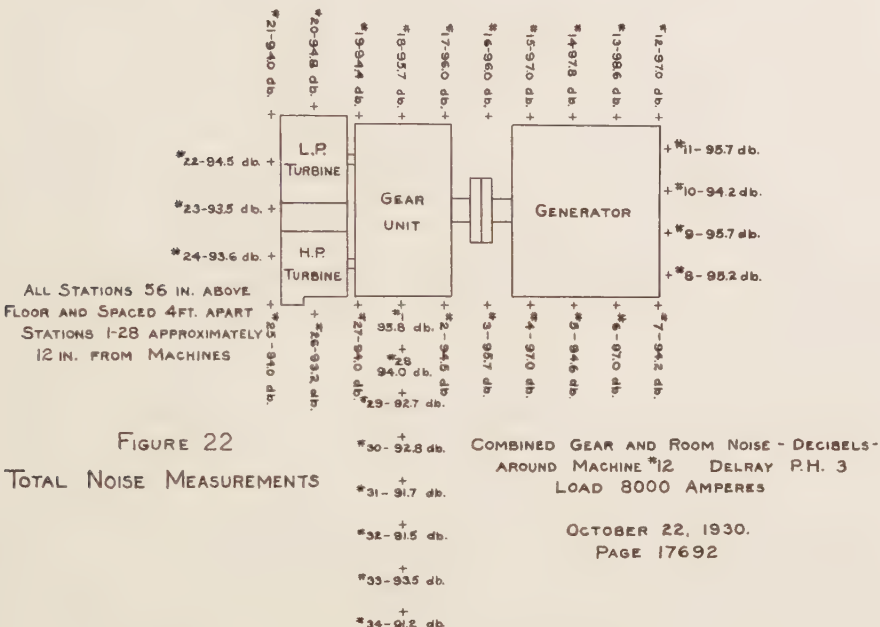


FIG. 22. Total noise measurements (not corrected for room noise) in the neighborhood of one of the large gear units showing the effects of room noise.

case made a difference of about 2.4 db. Table VI shows two consecutive sets of measurements taken on Machine 13 with the microphone at a distance of 6 inches and 8 inches, respectively.

These data are identical within the accuracy of measurement so that it does not appear that a slight difference in microphone location would affect the results obtained.

Effect of Load. All of the previously described measurements were taken at a constant load of 8,000 amperes on the generator, which represented about the normal operating loads of these machines. It was observed that the load on the gear unit produced a change in the

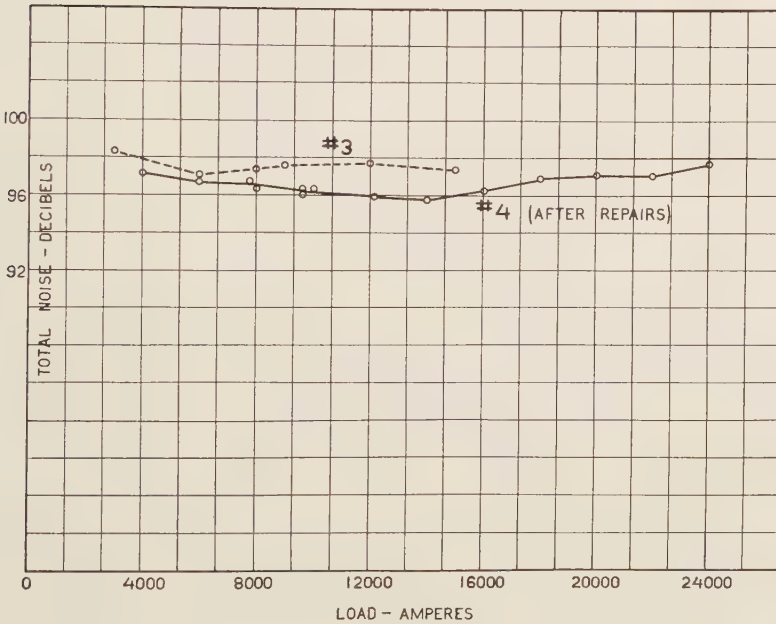
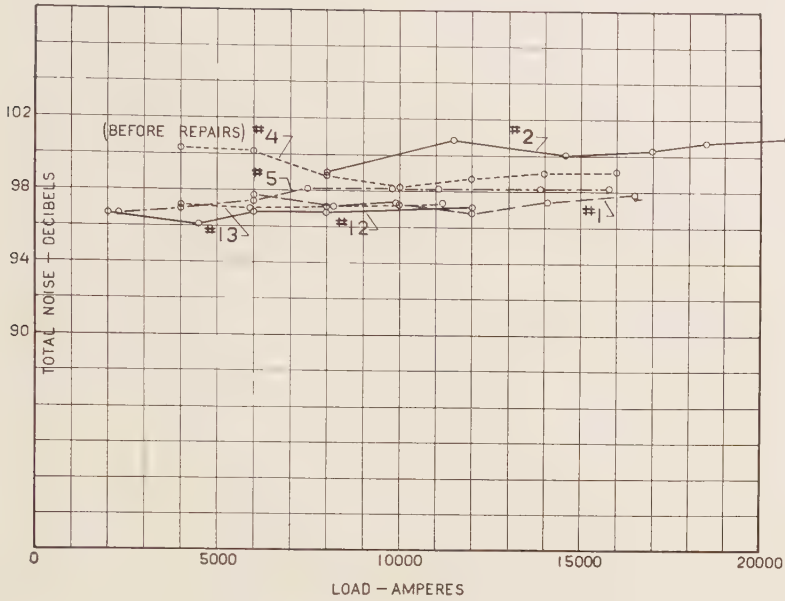
noise in the machine. Accordingly, total-noise measurements were made at several different loads for each of the machines. These data are shown in Figures 23, 24, and 25. These graphs show no very great changes of noise with load. As the load was increased, the noise of some of the machines decreased slightly, in others it increased, and in still others there was no appreciable change. This seems to be fairly representative of the effect of load on gear noise. From this it appears that there would probably be slight changes in the order of noisiness of these

TABLE VI
EFFECT OF MICROPHONE DISTANCE

Machine 13—Load 4000 amperes		
Station	Total Noise-Decibels Distance of Microphone from Gear Case	
	6 inches	8 inches
1	97.8	97.3
2	99.3	99.0
3	97.4	97.4
4	98.4	98.1
5	97.1	96.6
6	95.8	96.7
7	96.5	96.9
8	97.6	96.8
9	97.0	96.2
10	94.9	95.6
Average	97.2	97.1

gear units if they were compared at different loads. These changes are small in comparison with the differences between the quieter group of gears and the noisier group. Hence, it did not seem worth while to make a more complete study of the effect of load in this investigation.

Data on Checks of Repeat Runs. Time did not permit the running of check runs on the analyzed notes and the room noise readings, but the author believes that these readings were sufficiently accurate for the purpose of the investigation. This belief is strengthened by a few checks which were made on individual readings. In the course of setting up the equipment, several readings were taken on the 260-cycle note of Machine 2 as this was the most prominent note encountered. The values obtained on this note together with those of a couple of other repeat runs are shown in Table VII.



FIGS. 23 and 24. Load-Total Noise curves of large gear units. Not corrected for room noise.

These figures indicate that readings on analyzed notes could be repeated within about 1 db., which represents just about the uncertainty of measurement due to variations from point to point around the ma-

TABLE VII
CHECK BETWEEN REPEAT RUNS ON ANALYZED NOTES

Machine	No. 2				
Date	10/3	10/6	10/6	10/6	10/6
Time		A.M.	P.M.	P.M.	
Reading (db.)	94	94	92	93	94

Machine	No. 4		No. 6	
Date	10/7	10/7	10/16	10/16
Time	1:35	1:45	A.M.	P.M.
Reading (db.)	88	87	82	83

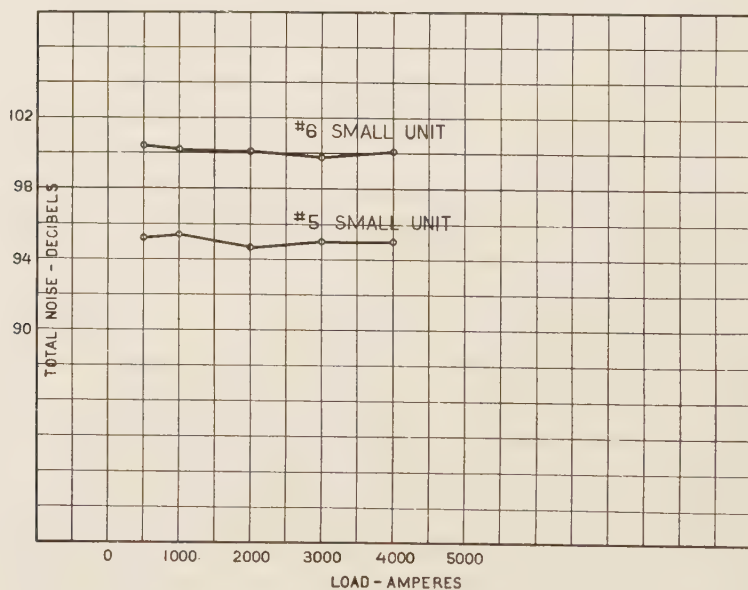


FIG. 25. Load-Total Noise curves of small gear units. Not corrected for room noise.

chine. A few consecutive repeat measurements on room noise checked within 0.1 db. which indicated that little error was encountered there.

At the time the measurements were made on Machine 4 to determine the effects of repairs, check readings were made on several other noises. These are shown in Table VIII.

The room noise at Machine 2 was about 3 db. less in January than it had been three months previously. This was due to the fact that the October measurements were taken with Machine 1 in operation while the January measurements were taken when Machine 1 was shut down. This accounted for the reduction in room noise at Machine 2. The room noise at Machine 4 was measured under identical conditions at both times and the values checked within 0.1 to 0.2 db., which was very grati-

TABLE VIII
COMPARISON OF MEASUREMENTS TAKEN AFTER A THREE-MONTHS INTERVAL

Ma- chine	Sound	Stations 1-10		Stations 13-18		Average	
		Oct. '30	Jan. '31	Oct. '30	Jan. '31	Oct. '30	Jan. '31
2	room	93.1	90.8	93.8	89.5	93.5	90.2
4	room	91.6	91.5	90.2	90.5	90.9	91.0
5	room	92.7	92.0	92.6	91.6	92.6	91.8
2	total	97.6	98.4	94.7	96.6	96.6	97.8
2	260 cycles	94	96	—	—	—	—
5	total	96.1	95.6	96.1	96.5	95.8	95.9

fyng. The room noise at Machine 5 was approximately 0.8 db. less in January than it was in October on account of the reduction in the noise of Machine 4 which was effected by repairs. The total noise of Machine 2 showed an increase during this period of 1.2 db. and the 260-cycle note, which was the principal source of sound on this machine, increased 2 db. which was just sufficient to account for the 1.2 db. increase in the total noise if the other noises had remained constant. The most careful check was made in the case of Machine 5. The average value of total noise of this machine checked within 0.1 db., which was a very close check, indeed. The consistency of these readings which were taken three months apart greatly increased the confidence of the author in the measurements taken.

Summary of Miscellaneous Tests. All of the miscellaneous tests described above were made to determine approximately what effects might be expected from some of the various factors which might have affected the readings. Time did not permit much study of these factors, but all of the results obtained indicate that measurements checked very closely enough that the results are entirely reliable, and suitable for the purpose for which they were taken.

Frequency-Response of Total Noise Meter and Microphone Calibration. The individual notes from the machines under test varied from 69 db. to 94 db. Fortunately the shape of the equal loudness contours do not vary greatly over this range, so it appeared that a loudness curve of about 80 db. would be quite suitable for the total-noise meter. The solid line of Figure 26 shows the combined characteristic of the amplifier and microphone as determined by thermophone calibration by the author. The solid circles are Kingsbury's¹ data for this contour, while

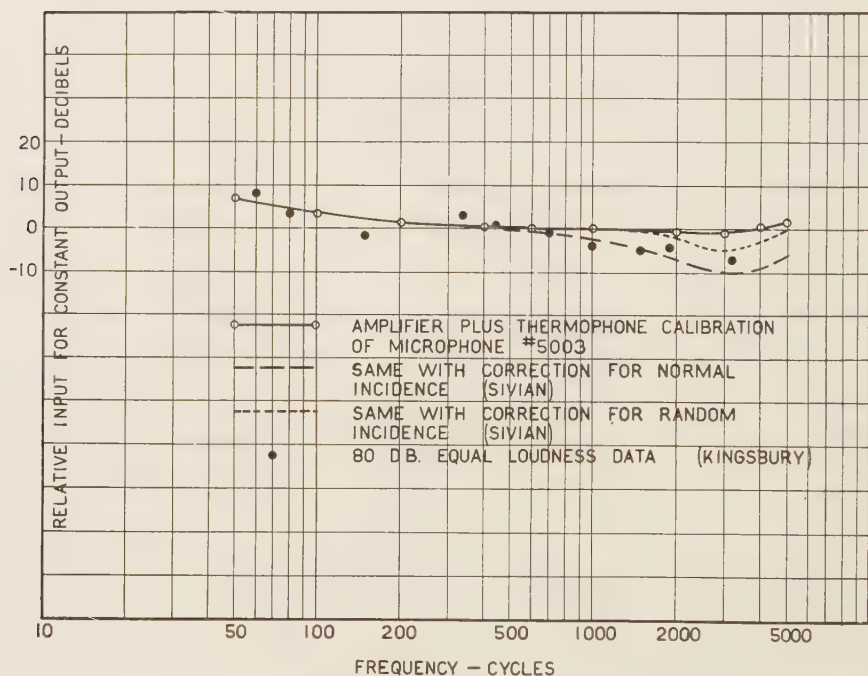


FIG. 26. *Frequency-response characteristic of soundmeter as used for measuring total noise.*

the dotted and dash curves give Sivian's field corrections for normal and random incidence.⁴ In the present case the sound came mostly from a hemisphere, so it is suspected that the proper correction might lie somewhere between the two. It appears that the agreement between the actual curve and the theoretical data about as close as one could hope to obtain. At any rate it is a perfectly definite relation which can be duplicated quite closely if necessary, and it is believed that it is suitable to the purpose for which it was used.

The differences between the sounds produced by the different gear

units were so small that it appeared desirable to determine the absolute calibration of the microphone within $\pm \frac{1}{2}$ db., and to within $\pm \frac{1}{4}$ db. if possible. Preliminary calibrations indicated that this was a rather difficult task, and it is planned to present the results of this phase of the work in a subsequent paper.

Day-to-day variations in microphone sensitivity of the order of $\pm \frac{1}{2}$ db. were observed, and it was suspected that the similar variations in total-noise readings as shown in Table I were probably due to fluctuations in the microphone sensitivity rather than in the sound. If this

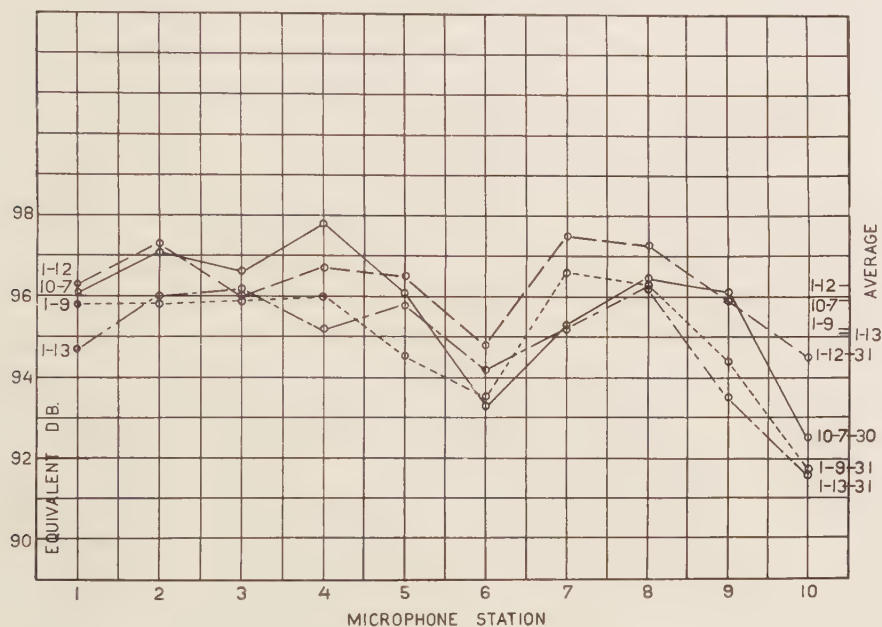


FIG. 27. Four different sets of total noise measurements (corrected from room noise) on Machine 5 showing the nature of the variations in individual readings.

were true, these variations should have been the same for all stations. An examination of the data showed that this was partially, but not entirely, the case. Figure 27 shows typical readings obtained at the individual stations on four independent runs on Machine 5. Three of these runs were taken within a week, and the fourth three months previously. It will be observed that all the curves bear a strong family resemblance, but that all the variations cannot be accounted for by shifts in microphone sensitivity. As a result, it is concluded that the procedure followed at the time of measurement was proper, and that the various runs on different days probably tended to average out shifts in micro-

phone sensitivity as well as the other variables. No evidence was found of long-time changes either in noise or in microphone sensitivity.

In the event of future measurements of this nature it is planned to calibrate the microphone in the field at least once a day, or more frequently if the occasion appears to demand it. It also appears that it would be worth while to obtain a microphone which is less sensitive to barometric and temperature changes if this is possible, even though this entails a shortening of the life of the microphone.

Summary and Conclusions. The data herein presented indicate that satisfactory noise specifications in terms of physical units can be obtained for this type of machine. The complicated questions of sound quality and the loudness characteristics of the average human ear were successfully treated in this case by specifying the noise in terms of four different characteristics. The so-called total noise was obtained by means of a microphone-amplifier-indicator system whose frequency-response was adjusted to the "equal loudness contour" of suitable level. The frequency spectrum of the sound from each machine was determined by means of an adjustable electrical frequency analyzer. Corrections were made for extraneous room noise and all of the data were expressed in terms of the sensation level of the equally-loud 1000-cycle tone as determined from Kingsbury's data.¹ From this it was possible to rate each machine according to four characteristics: the average total noise, the largest single note, the combined musical notes, and the unpitched sound. These four characteristics appeared to take account of the rather extreme differences in the quality of the sound among the different machines. The relative ratings of the various machines according to these four features were in perfect agreement with aural observations which could be made quickly by the observer passing from one machine to another. It is believed that this same sort of specification will be suitable for many types of machinery noise.

The total noise and the value of each component note varied greatly from point to point on the machines. These variations on a single machine were considerably greater than the differences between machines, and, as each machine showed a different pattern, it was impossible to obtain proper relative ratings by measurement at corresponding stations on the several machines. Measurements showed that proper relative ratings were obtained by averaging the values obtained at ten stations on each side of each machine. The reading obtained on a given machine varied somewhat from day to day, and consequently measurements were made on several days to average-out these effects. The noise produced by

a given machine was somewhat affected by load. The various machines behaved differently in this respect, some showing an increase, some a decrease, and others no particular change in the noise for a given change of load. In all cases the changes of noise with load were small, and it was felt that good relative ratings could be obtained at a single load.

The range of values represented by the eight large gear units tested was 3 db. for the total noise, 12 db. for the largest single note, 6 db. for the combined musical notes, and 1.5 db. for the unpitched sound. These appear at first to be very small differences, particularly in the case of the total noise. On the other hand it was possible to repeat average total-noise measurements on a given machine to within a few tenths of a decibel even after an interval of several months. The published information on the intensity discrimination of the average human ear for pure tones shows that the minimum perceptible difference at these levels is about .3 db. as compared to about 1 db. at lower levels. This difference, therefore, appears about the same as would one of 10 db. at more ordinary levels. This latter figure represents a very noticeable difference in the case of machinery noises. These measurements were checked rather carefully by "back and forth" observations by ear and also by comparisons of various loudness differences by ear. It was concluded that the data were consistent with themselves, with the aural observations, and with the published characteristics of the average human ear. The chief difficulty arising from these small differences was the question of absolute microphone calibration for specification purposes. Experiments indicate that the determination of the absolute sensitivity of a given microphone at the time of measurements closer than $\pm \frac{1}{2}$ db. is rather difficult. On the other hand this accuracy appears to be none too great for the purpose, which indicates that the microphone for such work must be rather carefully chosen and frequently checked.

The frequency analyses of the sound from these gear units showed a different set of musical notes for each machine. Considerable information concerning the sources of the noise was obtained by relating the frequencies of the observed notes to the movements of different parts of the machine. It was found that all of the important notes corresponded to multiples of the frequencies of rotation at the two pinion gears. The important harmonics ranged from the 3rd to about the 20th. The rotational frequencies themselves could not be detected nor could harmonics of the tooth-contact frequencies. The fundamental tooth-contact frequency could be detected on only two of the eight machines,

and in both of these cases it was so small as to be entirely negligible. This was a very surprising result in that it eliminated the most usual causes of gear noise, namely tooth form and errors in adjustment which produce tooth-contact notes. No notes whatever could be traced to the large gear so that its contribution to the noise, if any, must have been in the unpitched sound. This latter sound was not believed to be as important as the musical notes because all of the sets showed about the same amount of unpitched sound while the louder ones showed much larger values for the musical notes.

It was concluded quite early in the investigation that the musical notes were not due to resonances in the machine. Definite support for this conclusion was obtained by the repairs which were made to Machine 4. These repairs consisted in removing a small amount of material from one side of the gear teeth which operation produced an entirely different set of notes rather than a simple reduction in the magnitudes of those previously present. In as much as every part of the machine in which one could expect to find resonance was identical before and after repairs, the notes must have been due to errors in the gears rather than to resonances in the machine. An excellent agreement was found between the frequency analyses and the markings which were found on the teeth of Machine 4 when it was disassembled for inspection. Groups of spots showing abnormal tooth contact were found spaced in groups around the periphery of the opinions which exactly corresponded to the frequencies of the observed notes. From this it seemed almost certain that the principal sources of the noise existed in the machine on which the gears were cut, and that these errors were in the mechanism by which the tooth spiral was generated and the gear blank indexed from tooth to tooth.

From this it is seen that frequency analyses of machine noises not only furnish an important part of the information necessary for noise specification, but that they yield very definite and very valuable information concerning which parts of the machine are responsible for the various observed noises, and something of the nature of the errors which produce these noises.

REFERENCES

1. B. A. Kingsbury, Direct Comparison of Loudness of Pure Tones, *Physical Review*, April 1927, p. 588.
2. R. H. Galt, Results of Noise Surveys, *Jour. Acous. Soc. Am.* Vol. 2, No. 1, July 1930, p. 32.
3. H. Fletcher, *Speech and Hearing*, D. Van Nostrand Co., 1929, p. 158.
4. L. J. Sivian, Absolute Calibration of Condenser Transmitters (and attached bibliography). *Bell Syst. Tech. Jour.* Vol. X, No. 1, Jan. 1931, p. 96.

